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Parametric-based designs for kinetic facades to optimize daylight performance: Comparing rotation and translation kinetic motion for hexagonal facade patterns

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Abstract

Recent literature shows that experimentation in kinetics and architectural skins is more widely introduced as a solution for environmental-related design issues. Facades and elements are transformed in kinetic living creatures changing in synchrony with the surrounding environment. Through the lens of morphology, this research explores the possibilities of kinetic composition afforded by facades in motion. It presents a method for the evaluation of kinetic facades system performance using experimental approach. The experiments investigate improving daylight performance through the design and motion of kinetic facades using various integrated software. The impact of kinetic motion of hexagonal pattern on south-facing skin to control the daylight distribution in an office space is studied using parametric simulation technique. Results demonstrate the analysis of rotational and translation kinetic motions at the early design stage compared to a traditional window (base case). Finally, possible configurations to enhance daylight performance are suggested.
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Keywords: Kinetic facade; Daylight; Parametric design; Building skin

1. Introduction

Recent studies highlighted the significant effect of façade design on indoor day lighting quality (O'Brien et al., 2013; Sherif et al., 2012a; Shen and Tzempelikos, 2012; Freewan, 2014). A high integration of design and research between architects, computational designers, and consultants is important to address limitations associated with incorporating performance criteria in the design of façade by integrating different simulation tools (GhaffarianHoseini et al., 2013). Yet, it is still important to explore kinetic skin patterns for such integrated design (Baldinelli, 2009). Kinetic skin patterns are formed by multiple singular movements. Through the lens of morphology, this research explores the possibilities of kinetic composition afforded by façades in motion in terms of rotation and translation motion. Composition is analyzed in terms of pattern, defined as the relative movement of individual kinetic parts in time and space – the way in which multiple singular kinetic events cluster, or propagate, across a facade over time. Few studies investigated the impact of kinetic facades on indoor day lighting. There is a need to experimentally

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investigate such kinds of patterns. This study will be carried out to evaluate the performance of kinetic façades that integrate different motions in response to dynamic day lighting.

Through applying parametric modeling as a generative design and analysis tool, this paper examines the technical details linking system variables with daylight quality. Two hypotheses will be investigated. Firstly, kinetic skins can be designed and animated to reach optimal daylighting performance of buildings using the parametric modeling and simulation at early design phase. Secondly, rotation motion provides better illumination levels than translation motion in southern facade.

2. Background

2.1. From Façade to skin

Integration of elements produces a combined functionality that transcends the traditional notion of design. The concept of facade radically changed this process (Rafael, 2010). The façade is not just a neutral elevation that separates the inside and the outside of the building. Far beyond, the façade becomes an active element that makes the building interact with its context and the environment (Tzempelikos et al., 2007). This element is now considered as a continuous envelope of tectonic, environmental and aesthetical relationship between the interior and the exterior: *the skin*. (Bougiatioti et al., 2009; Rafael, 2010).

The design logic of architectural skins is based on a more sustainable approach through improving the energy performance of a building (Bougiatioti et al., 2009). The decisions about the geometrical forms, the materials, or the construction details, are made to moderate the energy exchange. The contemporary emphasis within architectural design on environmental performance has led to a renewal of interest in the capacity for a facade to be kinetically responsive (Ramzy and Fayed, 2011). A range of environmental sunscreens have been constructed, and new systems are continually being developed. At present the kinetics is basic, but there is no doubt that the current trajectory of research into responsive building facades will continue, with the result that more sophisticated technical solutions will be available (Favoino et al., 2014). Within these environmental systems there is a growing recognition that the aesthetics of the technology needs to be considered, alongside the technical performance (Moloney, 2011).

Research on the impact of solar screens on day lighting performance has received growing attention recently. Empirical study of day lighting performance was conducted for an existing typical government office in a hot-humid climate in Malaysia (Lim et al., 2012). This study indicated that simple modification of window glazing and shading device provides significant improvement in tropical day lighting quantity and quality for visual comfort. Previous studies in hot dry climates investigated the design of the influence of perforation percentage of Solar Screens on day lighting performance in a typical residential living room of a building in a desert location (Sherif et al., 2012c). They suggested minimum perforation percentages for Solar Screens for specific design cases that encompassed different orientations. Another study investigated the influence of changing the perforation percentage and depth of these screens on the annual energy loads, hence defining the optimum depth/perforation configurations for various window orientations (Sherif et al., 2012b). This study concluded that compared to traditional screens, lighter and deeper solar screen configurations were found to be more efficient in energy consumption. Most studies were based on static, rather than dynamic, solar screen systems. This research argues that utilizing dynamic (e.g. kinetic) solar screen system in the building envelope would contribute to day light and energy performance in buildings.

2.2. Kinetic envelope systems

In recent architectural design practice, kinetic architectural design can primarily be found in building envelopes or skins. This approach to designing architectural skins comprises the adoption of kinetic mechanisms for environmental adaptation and responsiveness. The term "Kinetic architecture" was introduced by William Zuk and Roger H. Clark in the early seventies when dynamic spatial design problems were explored in mechanical systems (Ramzy and Fayed, 2011).

Kinetic structures at a scale beyond media or environmental screens can be classified to three significant approaches (Moloney, 2011). The first approach is for Hoberman Associates, arguably the leading international design and construction consultancy in kinetics. He developed a mechanical, light and flexible structural system using a group of hinged units, to form movable designs. His aesthetic is dominated by a distinctive approach to engineering, which produces a singular, minimal motion as the structural component folds in on itself.

The second approach was founded by the MIT Kinetic Design Group, it provided a taxonomy of control systems for kinetics. Fox (2003) taxonomy of control systems outlines the various ways kinetic structure may be controlled. In terms of broad general kinetic categorization, Fox and Kemp (2009) grouped them into three categories: deployable, dynamic, and embedded. He describes the embedded system as one that exists within a larger architectural whole in a fixed location; the deployable as existing in a temporary location, which is easily transportable; and the dynamic system as existing within a larger architectural whole, but acting independently with respect to control of the larger context. The kinetic façade systems studied will be of the embedded type. The embedded system can be directly measured, and comparatively analyzed for quantitative values; it also has the most direct impact on the building users and their comfort by controlling such factors as light, thermal comfort, and ventilation.

The third approach in dynamic kinetic structures is suggested by Oosterhuis and Xia (2007). They outlined creating interactivity using Hyperbody'siA/Protospace software, which is based on flocking algorithms. Projects are generally conceived as a singular double-curved surface, with the kinetics based on deformation of the surface by pneumatic structure. In general, the projects focus on the mechanics of realization, with minimal exploration of the possible range of kinetics enabled by the technology. In terms of a theoretical contribution, the use of an agent based approach to the control mechanism used by Oosterhuis has synergies with the complex 'heuristic responsive indirect' type identified in Fox's taxonomy. But, again, the concept of a control mechanism based on self-organizing behavior, such as that achieved with flocking algorithms, while potentially useful in indicating one approach to control systems, is not explored in terms of conceiving the opportunity for kinetic composition (Moloney, 2011).

The concept of Kinetic architecture investigates a building's capacity of motion. However, more consideration of response to environmental conditions is required. Fox (2003) also sees the need for the environmental mediation systems stating, the implementation and integration of computational devices within architectural components as an environmental moderating system pose a new level of developmental opportunities. There is a critical need to focus such novel technologies toward an important architectural responsibility; namely, sustainable strategies in buildings. Industry and research efforts are quickly moving to this area. A common approach is to augment buildings with kinetic capability, allowing buildings to alter their physical shape in response to climate conditions (Beesley et al., 2006). The other approach is to augment physical space with sensing capability. Current intelligent kinetic systems arise from the isomorphic convergence of three key elements: mechanical engineering, embedded computation and responsive architecture.

Moloney design experiments were done through three stages (Moloney, 2011). Stage 1 was undertaken to identify the most distinctive compound kinetics that result from pairing the base kinetic transformations of translation, rotation and scaling. These produced similar compound types, of which four were selected – twist, roll, yaw and spring – as being the most distinctive. Twist, roll and yaw are well-known and precise types of compound transformations used in flight dynamics. This approach will be the foundation of various kinetic motions at the design stage and on which the research proceeds to test and evaluate possible configurations to optimize daylight performance.

Kinetic movements can always be reduced to three basic types of movement: translation, rotation and scaling. This classification is used regardless of where the hinge or joint is located and without considering gravity. Both of these, however, have major implications for the design (Schumacher et al., 2010). Combinations of transformations, such as translation and rotation producing a rolling motion, give rise to composite movement. The definition of kinetics included material deformation as an additional type of complex movement (Moloney, 2011). For the scaling motion, it is important to understand the potential materials that can be associated with it in order to select the right material in Diva, which was not studied yet. For the purposes of these experiments, kinetic type will be limited to test two basic geometric transformations. In the case of linear movement, so-called translation, the position of an object in space moves parallel to the coordinate axes in a consistent planar direction; while in the case of rotation, the object changes its orientation in space by rotating about the coordinate axes. For each of these kinds of movement, one can identify three degrees of freedom, depending on how the position or orientation of an object changes with respect to one, two or three coordinate axes. Geometric constraints can be applied to limit an object's degree of freedom (Moloney, 2011; Schumacher et al., 2010).

2.3. Simulation tools

Successful simulation of building performance is a challenging task and has been phrased as the art of performing the right type of virtual experiment with the right model and tool (Godfried, 2011). The problem with existing environmental simulation tools is that they were designed for static building elements. Traditional simulation tools are based on static design, where material properties are assumed as a constant, not a variable. However, in evaluating dynamic building performance, kinetic systems must be analyzed under a range of diverse conditions for proper system evaluation. The kinetic façade evaluation has integrated a few variables, which are simulated together in real-time (Sharaidin et al., 2012). It remains of paramount importance to develop adequate building performance simulation tools as there is a great demand for effective tools and instruments that can be used in the design process of kinetic façades (Nielsen et al., 2011; Shen and Tzempelikos, 2012; Liu et al., 2014).

2.4. Kinetic skin parameters

The patterns of planar model of the building skin are evaluated in terms of morphology, where the practical constraints of materials are not considered. Once the most significant planar zones are located, the parameters are subsequently developed in more detail, tuned to known algorithmic approaches to generate various patterns of motion. This facilitates a systematic production of animations to visualize the resultant pattern. The production of animations is undertaken in two stages. The first stage is where the kinetics at the scale of a part is combined and distinctive compound motions are selected (Figs. 1 and 2). The second stage is where kinetics is indexed to the control variables and simulation.

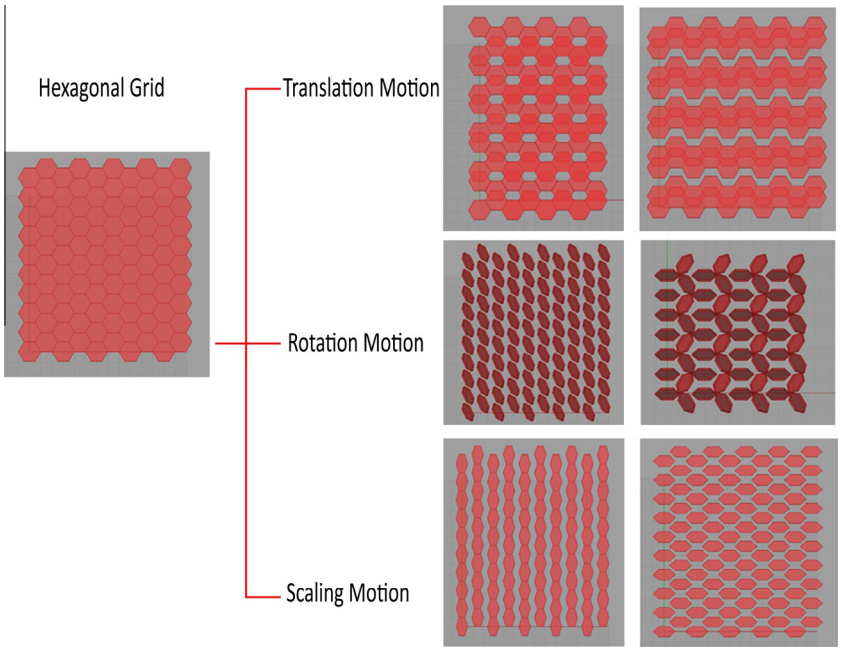


Fig. 1. The transformations of the hexagonal pattern using the three basic geometric transformations.

3. Method

Research work was divided into two consecutive phases. The first stage focuses on the analysis of daylighting performance for a window with standard dimensions of 3 m width × 1.2 m height. The Window–Wall-Ration (WWR) is set to 20% as the base case. The second stage represents a daylighting simulation using parametric tools for kinetic hexagonal-patterned façade to achieve the near optimum daylighting adequacy. In this case, the types of motion of hexagonal units are changed. The first type of motion is Rotation, which varies by changing the hexagons' angle of rotation. The other type of motion is translation, in which the units slide over one other. The kinetic motion daylighting simulations aimed to maximize daylighting performance. The simulation process allows us to choose the optimum design among these alternatives. This could be achieved through visualizing how kinetic façade systems work in relation to the space and to predict the final performance in the early design stage.

3.1. Study area

Cairo, Egypt was selected as the location. The location belongs to the Cairo and Delta bioclimatic zone (Mahmoud, 2011). Meteorological data are based on Cairo International Airport station (ETMY WMO Station 623660) based on 30 years average (1971–2000). Meteorological data show that summers in Cairo are hot and dry, while winters are dry and mild. The building orientation was south-facing to allow for maximum exposure of direct sun light. This criterion was important because it would help determine which kinetic system had enough variety to offer benefits during both the heating and cooling periods, rather than being beneficial to only one.

3.2. Parametric office model

A side-lit office space has been constructed as base model. The area is 45 m sq. and dimensions of 6.0 m width, 7.5 m depth and 3.0 m height, facing the south direction and located at the first floor. Though the facade configuration changes, the space dimensions remain the same throughout the entire study. Initially, the simulation is run for clear and overcast skies for the different types of motion test. The interior surfaces have been assigned a reflectance of 80% for ceiling, 50% for walls, and 20% for floor. The kinetic skin has silver matte material. The opening has been assigned doubled-glazed material with 80% visual transmittance. The kinetic skin is an external layer of double façade type which acts as a shading screen coupled with glazed interior layer with in-between buffer 30 cm. This office space was chosen so that each of the systems could be consistently compared (Figs. 3 and 4).

3.3. Kinetic hexagonal patterns

The façade has an array of hexagonal movable pattern as a general design pattern. According to Moloney (2011) pilot study, the hexagon shape gives a good combination of edge detection and contrast between shaded areas. Besides, it provides a relatively neutral orientation when a large number were combined in an offset (Moloney, 2011). Therefore, the kinetic motion was tested on hexagonal planar uniform tiling of identical modules of fixed cell radius 0.5 m for the purpose of study. The parametric

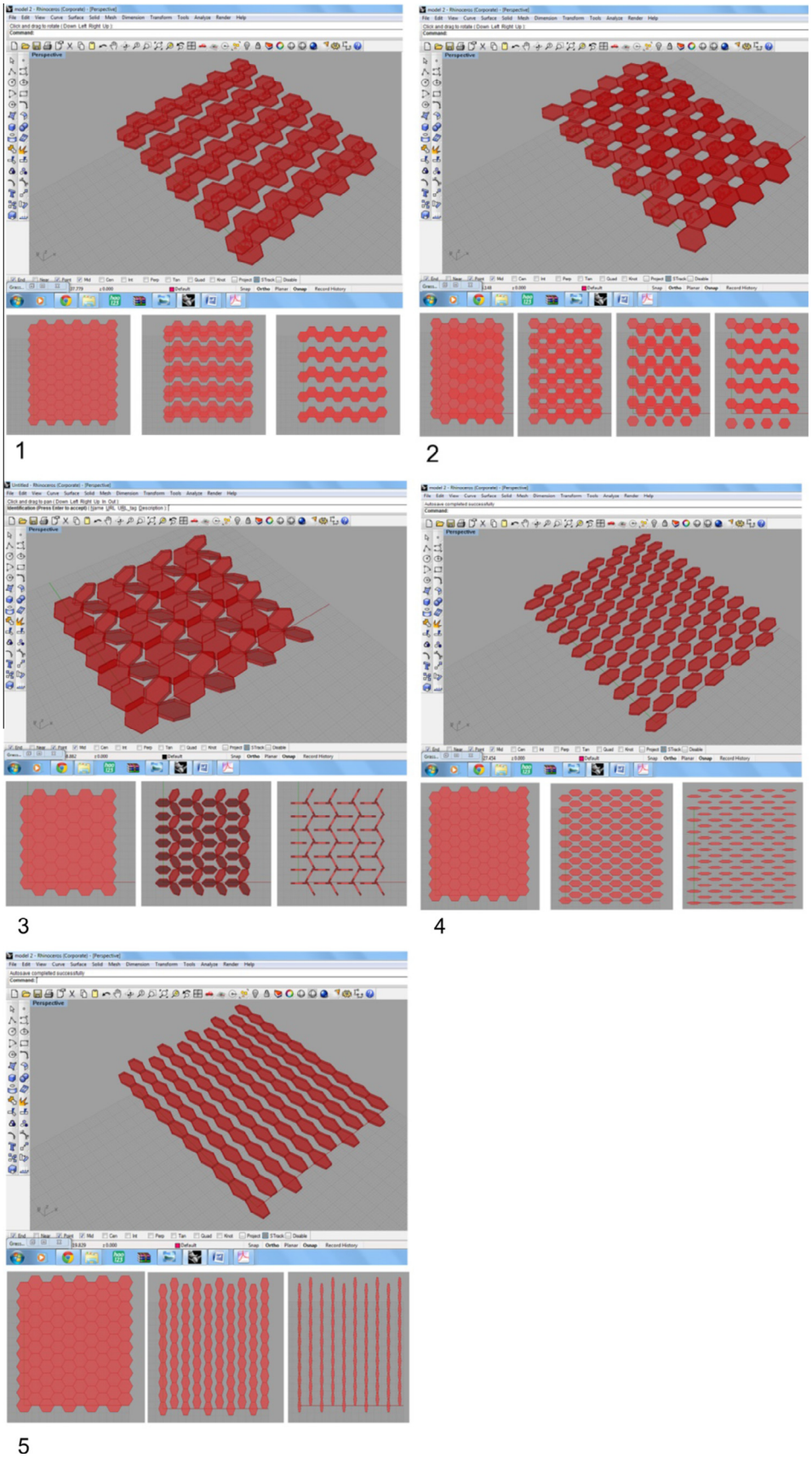


Fig. 2. The transformations of the hexagonal pattern; 1 & 2. Sliding, 3. Rotation, 4 & 5. Scaling in Rhino interface.

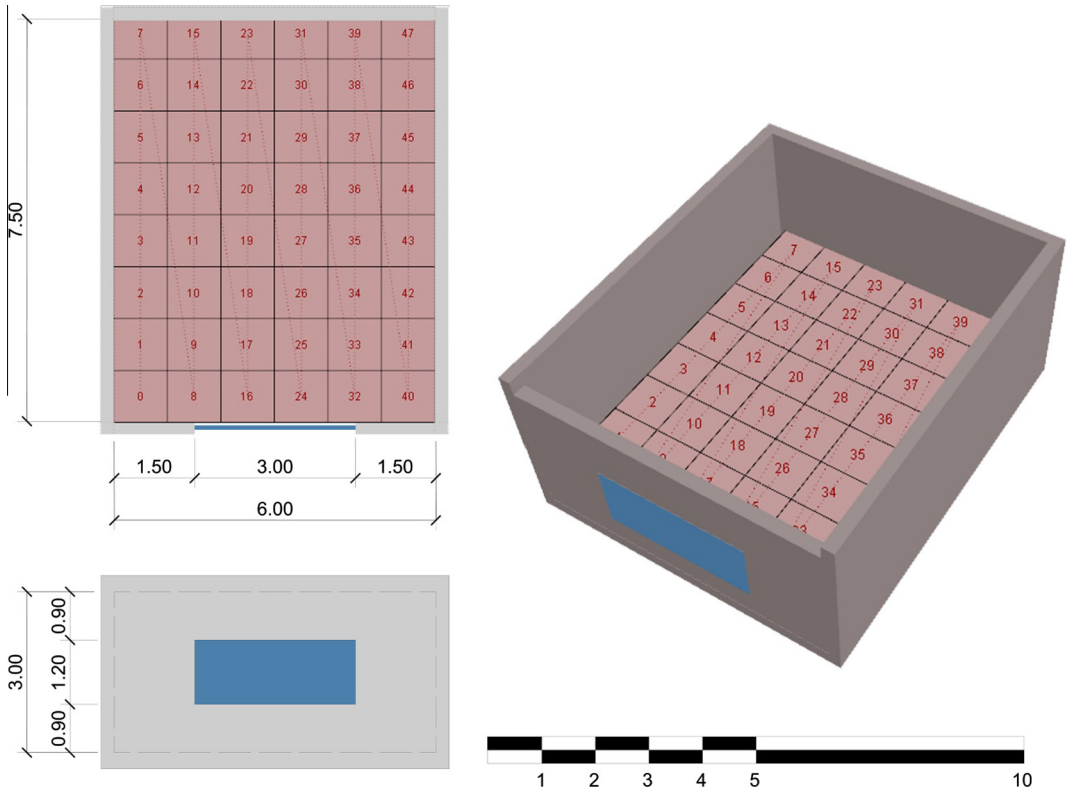


Fig. 3. South-facing office Space with dimensions 6.0 m width, 7.5 m depth, and fully-glazed height of 3.0 m on one side.

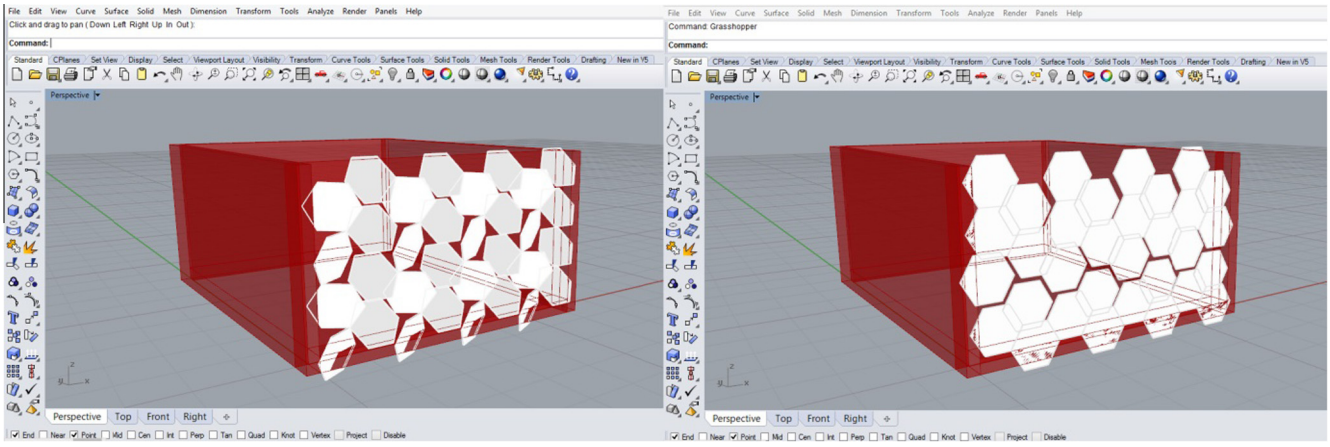


Fig. 4. Pattern definition – modeling using grasshopper shows the hexagonal cells that act as a kinetic pattern along with the room dimensions.

definition of the module as a unit was embedded in the design of the multiplication pattern along with its variable rotation or translation motion in an attempt to explore the impact of the kinetic system as a whole. The parameters were represented by "sliders" in Grasshopper application, with set minimum and maximum values depending on design requirements. In rotation motion, the hexagonal unit rotates around its centroidal axis ranging from 30 to 165 deg with a step size of 15 deg, while in translation motion, the unit slides over the other moving from center to center to be totally opened, this distance is divided into 10 steps (Fig. 5).

3.4. Daylighting simulations

Simulations for daylighting performance is planned to be studied for the three studied cases; the base case, the rotational & the translational kinetic motions. Previous studies used LEED v4 day lighting as a design standard (Heidarinejad et al., 2014; Moschetti et al., 2015). The simulation process conducted in this paper complied with LEED V4 daylighting requirement in which the three illumination evaluation levels for the floor area were used: "daylit", "partially daylit" and "overlit" areas. The "Daylit" area achieves illuminance levels between 300 lux

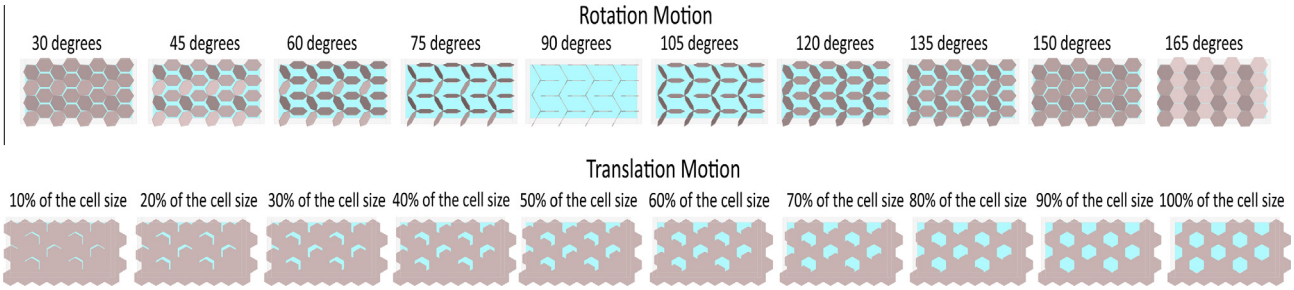


Fig. 5. Pattern transformation of the ten cases for both rotation and translation motion.

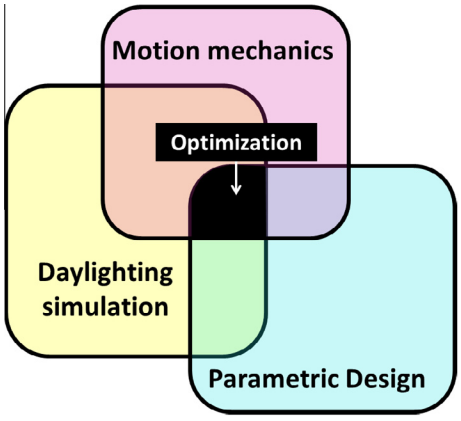


Fig. 6. Diagram show the integration between several fields; parametric design, motion mechanics and simulation technique; to reach optimal solution for kinetic skins.

and 3000 lux for the floor area; "Overlit" area achieves illuminance greater than 3000 lux for the floor area with potential glare; "Partially lit" area achieves illuminance below 300 lux for the floor area.

The simulation parameters was set to measure daylight illuminance sufficiency for the room, DIVA parameters were set to calculate the percentage of analysis points that achieves illuminance levels between 300 lux and 3000 lux for the floor area. The design for the building project shall demonstrate target illuminance (300 lux), according to ASHRAE Standard 90.1–2010 and the IES recommended range for office spaces. A daylight system was setup for Cairo, Egypt, with clear sky conditions, iterative runs were performed for each system, each run was planned to be performed for four days of the year, March 21, June 21, September 21 and December 21, at three h of the day, 9:00 am, 12:00 pm, and 3:00 pm. These dates and times were chosen so that a fairly accurate idea of the performance could be taken into account by encompassing the sun's highest and lowest altitude and furthest north and south azimuth angles range throughout each day.

3.5. Simulation parameters and procedure

In order to study the effectiveness of the kinetic motions, a number of computer simulations will be analyzed and compared. Simulating intelligence in building skins and testing it for dynamic day lighting performance is a challenging study in terms of simulation parameters and the logic of data processing. The main objective of the process and parametric algorithm is to evaluate the performance of kinetic skins in integrating different motions in response to

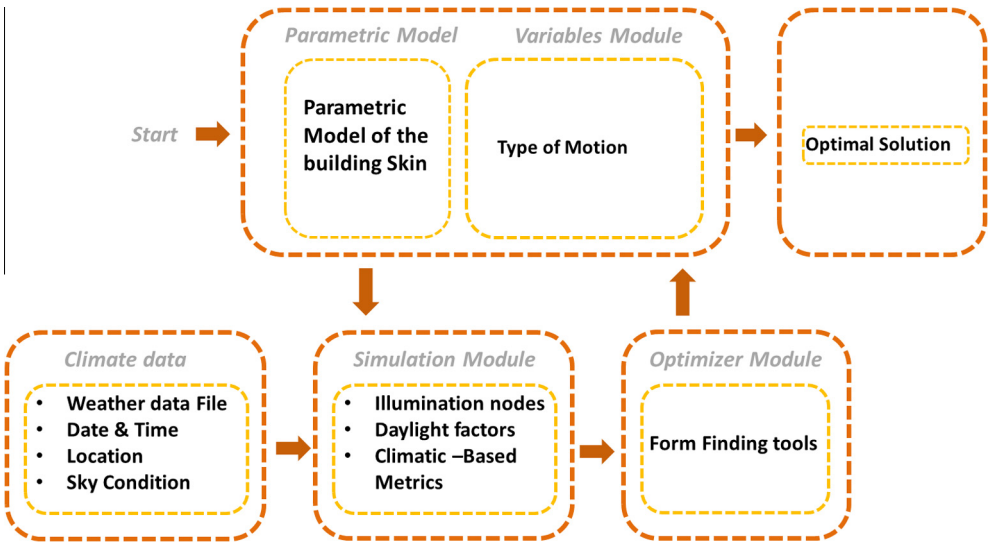


Fig. 7. A framework – the path of data between the proposed algorithm and day lighting simulation tool.

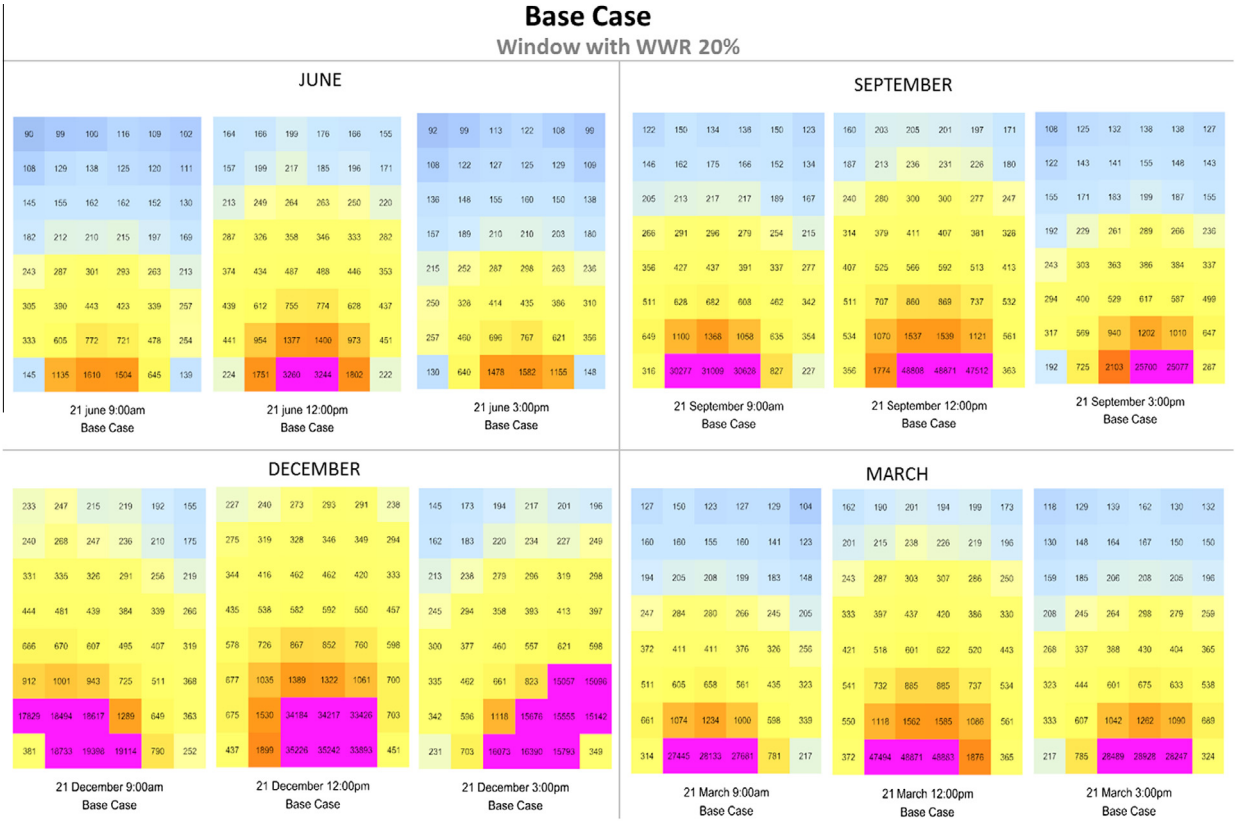


Fig. 8. Daylighting simulation using Diva for Rhino for the base case analyzed in terms of illumination evaluation levels.

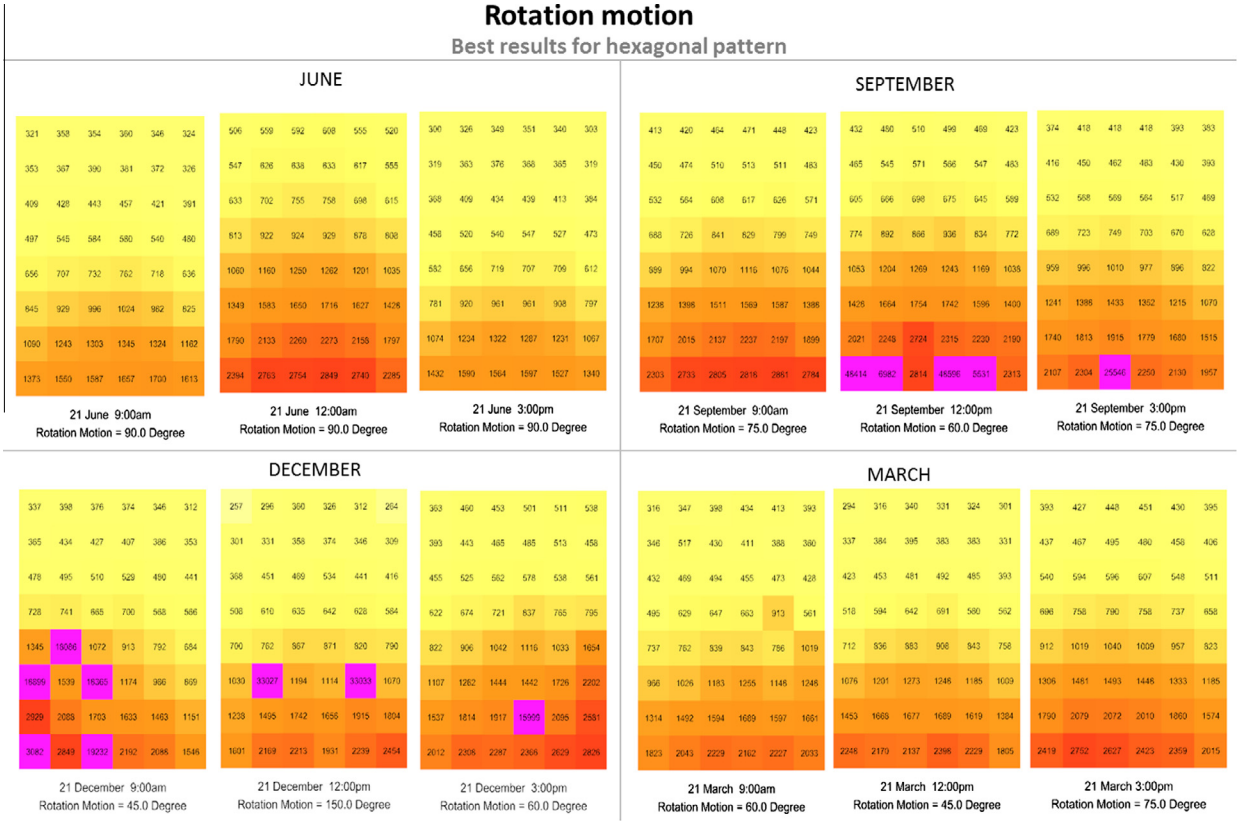

Rotation motion
Best results for hexagonal pattern
JUNE
SEPTEMBER
21 June 9:00am Rotation Motion = 90.0 Degree
21 June 12:00am Rotation Motion = 90.0 Degree
21 June 3:00pm Rotation Motion = 90.0 Degree
21 September 9:00am Rotation Motion = 75.0 Degree
21 September 12:00pm Rotation Motion = 60.0 Degree
21 September 3:00pm Rotation Motion = 75.0 Degree
DECEMBER
MARCH
21 December 9:00am Rotation Motion = 45.0 Degree
21 December 12:00pm Rotation Motion = 150.0 Degree
21 December 3:00pm Rotation Motion = 60.0 Degree
21 March 9:00am Rotation Motion = 60.0 Degree
21 March 12:00pm Rotation Motion = 45.0 Degree
21 March 3:00pm Rotation Motion = 75.0 Degree

Fig. 9. Daylighting simulation using Diva for Rhino for the rotation motion best cases analyzed in terms of illumination evaluation levels.

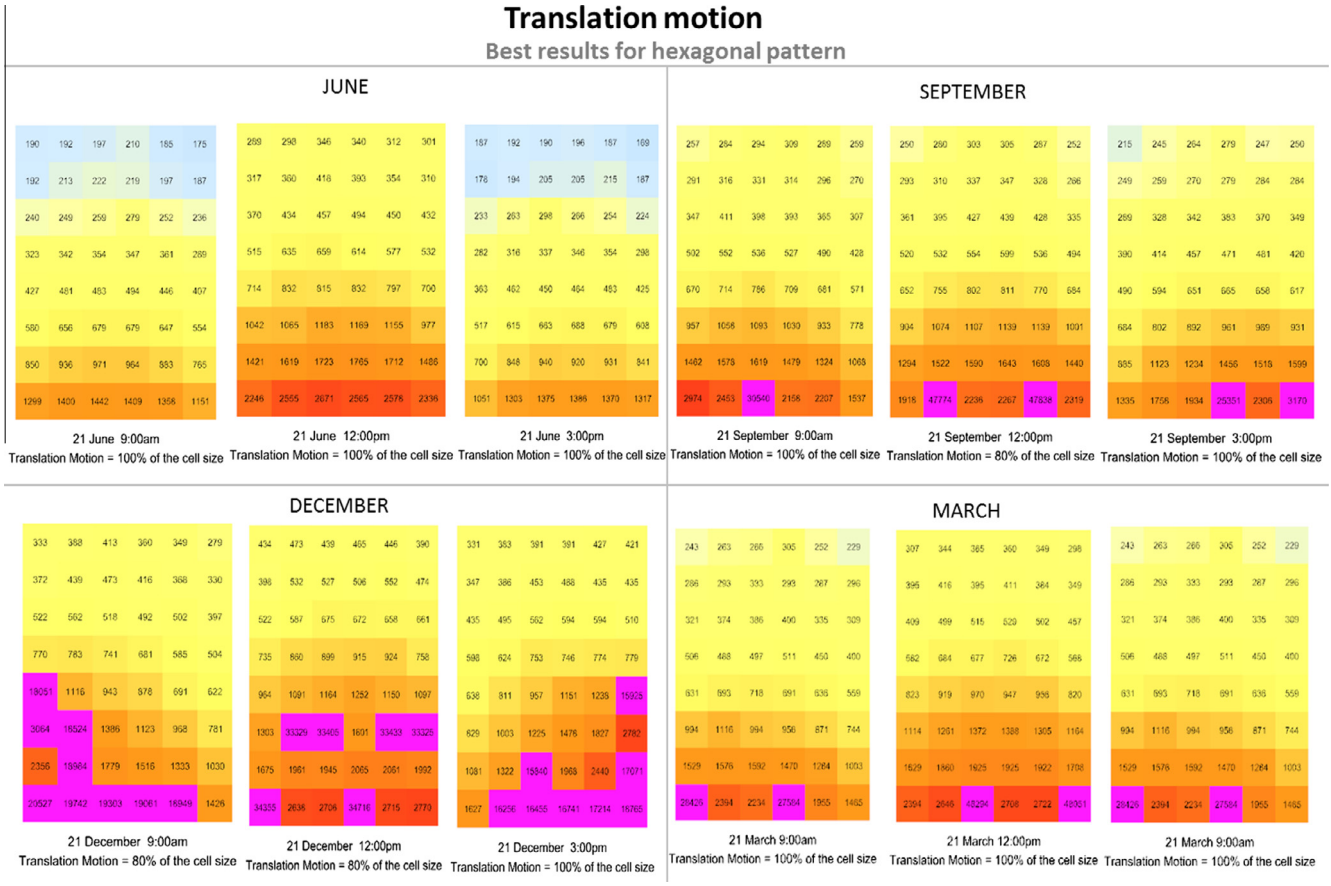

Translation motion
Best results for hexagonal pattern
JUNE
SEPTEMBER
21 June 9:00am
Translation Motion = 100% of the cell size
21 June 12:00pm
Translation Motion = 100% of the cell size
21 June 3:00pm
Translation Motion = 100% of the cell size
21 September 9:00am
Translation Motion = 100% of the cell size
21 September 12:00pm
Translation Motion = 80% of the cell size
21 September 3:00pm
Translation Motion = 100% of the cell size
DECEMBER
MARCH
21 December 9:00am
Translation Motion = 80% of the cell size
21 December 12:00pm
Translation Motion = 80% of the cell size
21 December 3:00pm
Translation Motion = 100% of the cell size
21 March 9:00am
Translation Motion = 100% of the cell size
21 March 12:00pm
Translation Motion = 100% of the cell size
21 March 9:00am
Translation Motion = 100% of the cell size

Fig. 10. Daylighting simulation using Diva for Rhino for the translation motion best cases analyzed in terms of illumination evaluation levels.

dynamic daylighting and search for an optimal solution for kinetic skin configurations (Fig. 6).

This research presents an algorithmic and parametric design process developed in Rhino/Grasshopper and DIVA-for-Rhino. The integration of these three tools was necessary for the objective of this study: Rhino as a modeling tool, Grasshopper as a parametric interface, and DIVA-for-Rhino for daylight evaluation. Rhino modeling application has been used in several studies including design and generate documents for the construction of a complex façade (Moya and Pons, 2014); design of deployable scissor shelter (Mira et al., 2014) and the design of solar screen designs to achieve visual comfort (Sabry et al., 2014). Similarly, Grasshopper parametric interface application has recently been used in building simulations (Greenberg et al., 2013). Grasshopper parametric definition is used to bridge the gap between the early design stage and the energy-performance of the building, in terms of daylighting. Grasshopper applications is used to identify the input parameters of the building skin and set the evaluation criteria for daylighting assessment; and pass these to the daylighting simulation tool, Diva application, to simulate the process of daylighting and sends the results back to Grasshopper for evaluation until an optimal solution is reached. These tools are selected based on the possibilities for integrating them together to run at the same time to get real time feedback (Fig. 6) (Fig. 7). Rationalizing the logic processing in the form of parameters is the key element for the success of the simulation process.

4. Results

Results of simulations for daylighting performance were analyzed for the base case as well as the two kinetic systems. The data output from the program was for 48 points, each is on a work plane of 0.9 m height and a grid size of 0.9×0.9 m, giving the total amount of luminance and illuminance on the surface in lux. This data is planned to be input into a spreadsheet for comparison between the three studied cases. The daylighting simulations helped in understanding the general tendency of each of the motion types' impact on the overall daylighting performance compared to the traditional window.

4.1. Results of stage one: base case

In this stage, the base case was evaluated for daylighting adequacy (Figs. 8 and 11). In summer, nearly half of the

Table 1
Comparison of percentages of daylit area for the Rotational motion different angles performed at four days of the year.

			Rotation Motion									
			R30.0	R45.0	R60.0	R75.0	R90.0	R105.0	R120.0	R135.0	R150.0	R165.0
June	9:00	Partially Daylit	58	33	17	4	0	6	23	42	63	88
		Daylit	42	67	83	96	100	94	77	58	38	13
		Overlit	0	0	0	0	0	0	0	0	0	0
	12:00	Partially Daylit	38	4	0	0	0	0	0	10	50	65
		Daylit	63	96	100	100	100	100	100	90	50	35
		Overlit	0	0	0	0	0	0	0	0	0	0
	3:00	Partially Daylit	48	21	0	0	0	0	0	4	40	67
		Daylit	52	79	100	100	96	100	98	92	56	33
		Overlit	0	0	0	0	4	0	2	4	4	0
September	9:00	Partially Daylit	46	21	0	0	0	0	0	15	50	73
		Daylit	52	75	100	100	88	98	96	81	46	27
		Overlit	2	4	0	0	13	2	4	4	4	0
	12:00	Partially Daylit	38	4	0	0	0	0	0	0	29	63
		Daylit	63	92	92	81	79	79	90	92	63	38
		Overlit	0	4	8	19	21	21	10	8	8	0
	3:00	Partially Daylit	48	21	2	0	0	0	0	13	44	67
		Daylit	52	79	96	98	98	96	96	83	50	31
		Overlit	0	0	2	2	2	4	4	4	6	2
December	9:00	Partially Daylit	33	0	0	0	0	0	0	0	33	69
		Daylit	58	92	85	75	77	77	77	90	60	25
		Overlit	8	8	15	25	23	23	23	10	6	6
	12:00	Partially Daylit	29	0	0	0	0	0	0	0	4	52
		Daylit	67	92	73	67	65	65	69	77	92	48
		Overlit	4	8	27	33	35	35	31	23	4	0
	3:00	Partially Daylit	44	15	0	0	0	0	0	0	27	63
		Daylit	50	77	98	88	79	77	79	81	67	38
		Overlit	6	8	2	13	21	23	21	19	6	0
March	9:00	Partially Daylit	46	17	0	0	0	0	0	21	50	75
		Daylit	54	79	100	100	96	96	100	75	46	25
		Overlit	0	4	0	0	4	4	0	4	4	0
	12:00	Partially Daylit	40	2	0	0	0	0	0	0	29	63
		Daylit	60	98	96	83	77	79	90	92	67	38
		Overlit	0	0	4	17	23	21	10	8	4	0
	3:00	Partially Daylit	48	21	0	0	0	0	0	4	40	67
		Daylit	52	79	100	100	96	100	98	92	56	33
		Overlit	0	0	0	0	4	0	2	4	4	0

base case floor area was found "partially daylit", while the other half was found "daylit" area. On the other hand, in winter, the "overlit" is relatively high and nearly half of the area was found "daylit" area, while, the other half was divided into "overlit" and "partially daylit" area. This means that in case of traditional window, there is only 50% of the space was adequate for most of the year.

4.2. Results of stage two: performance of studied kinetic facade

In this stage, the results of the kinetic cases were evaluated for daylighting adequacy. Ten cases are tested for four times of the year, at three hours of the day. Results of 120 cases formed by motion variations at previously mentioned dates for each kinetic case are analyzed. In rotation motion, the cases ranges from 30 to 165 deg with a step size of 15 deg, while in translation motion, the ten cases lies between the totally closed and the totally opened (Figs. 9 and 10).

All the kinetic tested cases resulted in acceptable daylighting performance and achieved a daylighting performance better than the base case. It was found that the "daylit" area increased significantly with a relative decrease in the "partially daylit" area in the summer while increasing the "daylit" area with a relative decrease in the

"over-lit" area in winter. The cases that represented the best daylight performance were highlighted with a light tone in Tables 1 and 2.

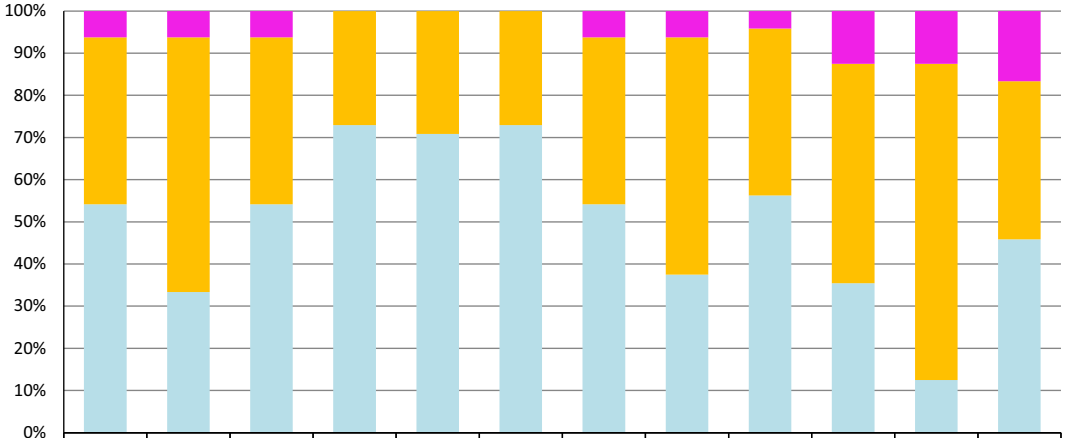
The rotation case was found acceptable at all timings where the "daylit" area percentage reached 90% of the space at the values ranges from R45 to R150 of the rotation motion design, as shown in Table 2. In June, the fully opened type of the rotation motion (90 deg) gives the most appropriate "daylit" area while the partially opened type (45 deg and 60 deg) increase the "daylit" to almost 100% in December and March (Figs. 9 and 10).

In translation motion, acceptable daylight performance was only achieved at fully opened case and partially opened of 60% in winter time. Although translation motion recorded some acceptable results, as shown in Table 2, where the "daylit" area percentage reached 90% at the middle of the day (12:00 pm) yet its performance in both early morning (9:00 am) and afternoon (3:00 pm) was found to be relatively low, mostly below 75% (Figs. 12 and 13).

In general, results indicate a major influence of pattern parameters and types of motion on the overall daylighting performance of office spaces. Both Kinetic screens helped improve the daylighting performance that acts as shading devices to control the excessive daylight level. It is clear that the over lit area is relatively high in winter time and mainly concentrated at four hours of the day. In the base case, the "Over-lit" area reached respectively 13% in winter while it was found that the kinetic rotation motion type

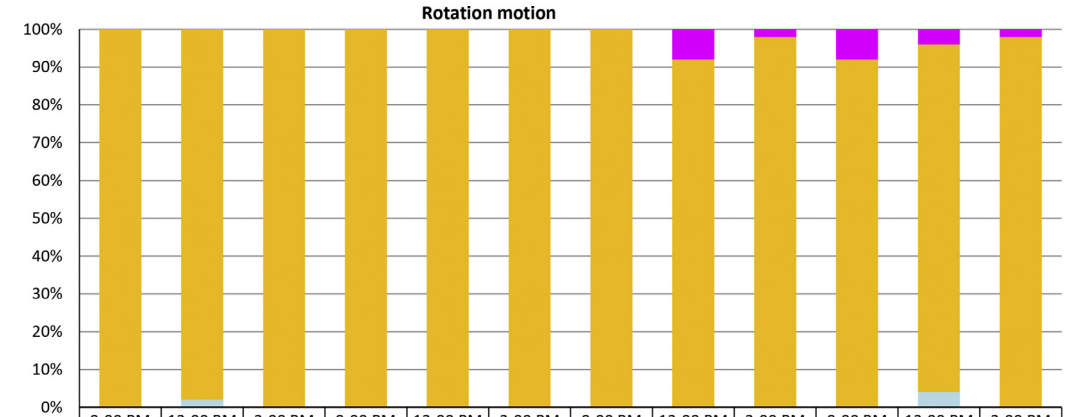
Table 2
Comparison of percentages of daylit area for the translational motion different movements performed at four days of the year.

			Translation Motion									
			T0.1	T0.2	T0.3	T0.4	T0.5	T0.6	T0.7	T0.8	T0.9	T1.0
June	9:00	Partially Daylit	100.00	100.00	87.50	75.00	66.67	62.50	54.17	47.92	41.67	41.67
		Daylit	0.00	0.00	12.50	25.00	33.33	37.50	45.83	52.08	58.33	58.33
		Overlit	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	12:00	Partially Daylit	100.00	87.50	75.00	62.50	50.00	39.58	33.33	20.83	14.58	6.25
		Daylit	0.00	12.50	25.00	37.50	50.00	60.42	66.67	79.17	85.42	93.75
		Overlit	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	3:00	Partially Daylit	100.00	100.00	89.58	77.08	70.83	62.50	54.17	50.00	43.75	39.58
		Daylit	0.00	0.00	10.42	22.92	29.17	37.50	45.83	50.00	56.25	60.42
		Overlit	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
September	9:00	Partially Daylit	100.00	85.42	66.67	58.33	50.00	39.58	37.50	29.17	18.75	14.58
		Daylit	0.00	14.58	33.33	39.58	47.92	58.33	60.42	68.75	79.17	83.33
		Overlit	0.00	0.00	0.00	2.08	2.08	2.08	2.08	2.08	2.08	2.08
	12:00	Partially Daylit	97.92	77.08	62.50	52.08	39.58	33.33	25.00	12.50	2.08	2.08
		Daylit	2.08	18.75	33.33	43.75	56.25	62.50	70.83	83.33	89.58	89.58
		Overlit	0.00	4.17	4.17	4.17	4.17	4.17	4.17	4.17	8.33	8.33
	3:00	Partially Daylit	100.00	91.67	77.08	66.67	58.33	50.00	43.75	37.50	31.25	27.08
		Daylit	0.00	8.33	22.92	33.33	41.67	47.92	54.17	60.42	66.67	68.75
		Overlit	0.00	0.00	0.00	0.00	0.00	2.08	2.08	2.08	2.08	4.17
December	9:00	Partially Daylit	93.75	70.83	54.17	41.67	31.25	20.83	4.17	0.00	0.00	0.00
		Daylit	6.25	29.17	45.83	52.08	58.33	68.75	79.17	81.25	81.25	81.25
		Overlit	0.00	0.00	0.00	6.25	10.42	10.42	16.67	18.75	18.75	18.75
	12:00	Partially Daylit	91.67	64.58	45.83	33.33	22.92	4.17	0.00	0.00	0.00	0.00
		Daylit	8.33	31.25	50.00	62.50	68.75	87.50	87.50	87.50	83.33	79.17
		Overlit	0.00	4.17	4.17	4.17	8.33	8.33	12.50	12.50	16.67	20.83
	3:00	Partially Daylit	97.92	75.00	64.58	52.08	41.67	29.17	14.58	8.33	2.08	0.00
		Daylit	0.00	22.92	29.17	37.50	45.83	54.17	68.75	75.00	81.25	83.33
		Overlit	2.08	2.08	6.25	10.42	12.50	16.67	16.67	16.67	16.67	16.67
March	9:00	Partially Daylit	100.00	100.00	87.50	77.08	66.67	62.50	54.17	50.00	43.75	37.50
		Daylit	0.00	0.00	12.50	22.92	33.33	37.50	45.83	50.00	56.25	62.50
		Overlit	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	12:00	Partially Daylit	100.00	77.08	64.58	50.00	39.58	33.33	22.92	14.58	4.17	0.00
		Daylit	0.00	22.92	35.42	50.00	60.42	66.67	77.08	81.25	91.67	95.83
		Overlit	0.00	0.00	0.00	0.00	0.00	0.00	0.00	4.17	4.17	4.17
	3:00	Partially Daylit	97.92	89.58	75.00	64.58	56.25	43.75	37.50	31.25	25.00	20.83
		Daylit	2.08	10.42	25.00	35.42	43.75	56.25	62.50	64.58	70.83	75.00
		Overlit	0.00	0.00	0.00	0.00	0.00	0.00	0.00	4.17	4.17	4.17



	9:00 PM	12:00 PM	3:00 PM	9:00 PM	12:00 PM	3:00 PM	9:00 PM	12:00 PM	3:00 PM	9:00 PM	12:00 PM	3:00 PM
	21-Mar			21-Jun			21-Sep			21-Dec		
Overlit	6.3	6.3	6.3	0.0	0.0	0.0	6.3	6.3	4.2	12.5	12.5	16.7
Daylit	39.6	60.4	39.6	27.1	29.2	27.1	39.6	56.3	39.6	52.1	75.0	37.5
Partially Daylit	54.2	33.3	54.2	72.9	70.8	72.9	54.2	37.5	56.3	35.4	12.5	45.8

Fig. 11. The base case simulation results in terms of illumination evaluation levels: "daylit", "partially daylit" and "over lit" areas.

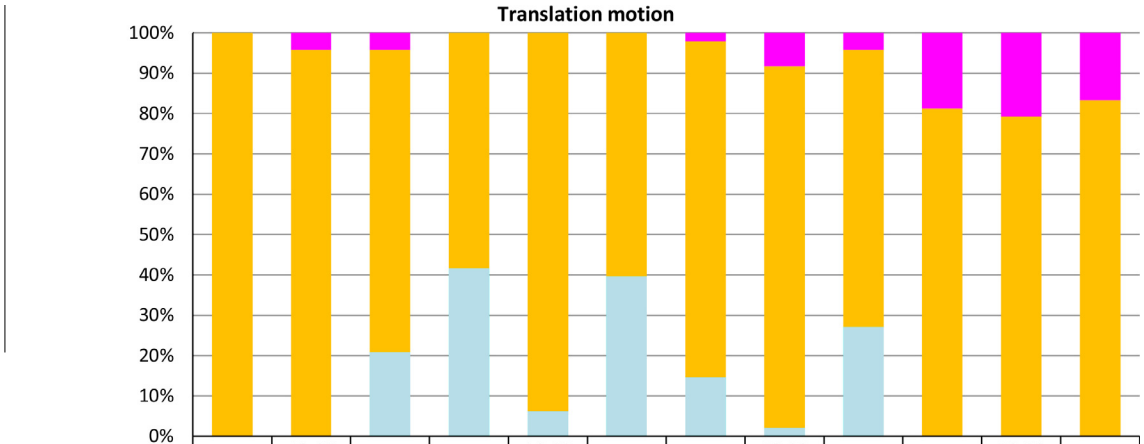


	9:00 PM	12:00 PM	3:00 PM	9:00 PM	12:00 PM	3:00 PM	9:00 PM	12:00 PM	3:00 PM	9:00 PM	12:00 PM	3:00 PM
	21-Mar			21-Jun			21-Sep			21-Dec		
Overlit	0	0	0	0	0	0	0	8	2	8	4	2
Daylit	100	98	100	100	100	100	100	92	98	92	92	98
Partially Daylit	0	2	0	0	0	0	0	0	0	0	4	0
Angle of rotation	R60 R75 R120	R45	R60 R75 R105	R90	R60 R75 R90 R105 R120	R60 R75 R105	R60 R75	R45 R60	R75	R90 R45	R45	R60

Fig. 12. The best simulation results of rotation motion in terms of illumination evaluation levels: "daylit", "partially daylit" and "over lit" areas.

performed better at R45, R60 and R150 deg to decrease the over lit area to reach a maximum value of 4% resulting in an appropriate "daylit" area. While in case of translational motion, the "over lit" area reached its maximum value 21% in winter at 12:00 pm in the fully opened pattern and could be reduced to 8% using the partially opened type (60%). This confirmed the notion that a Kinetic facade reduce over-lighting due to control of direct solar penetration as shown in Table 3 and Fig. 14.

To summarize, the climatically advantageous kinetic motion was the rotational rather than the translational. By comparing graphically analysis of daylighting



	9:00 PM	12:00 PM	3:00 PM	9:00 PM	12:00 PM	3:00 PM	9:00 PM	12:00 PM	3:00 PM	9:00 PM	12:00 PM	3:00 PM
	21-Mar			21-Jun			21-Sep			21-Dec		
Overlit	0	4.2	4.2	0	0	0	2.1	8.3	4.2	18.8	20.8	16.7
Daylit	62.5	95.8	75	58.3	93.8	60.4	83.3	89.6	68.7	81.2	79.2	83.3
Partially Daylit	0	0	20.8	41.7	6.2	39.6	14.6	2.1	27.1	0	0	0
Transtation motion	T 100%	T 100%	T 100%	T 100%	T 100%	T 100%	T 80% T 90% T 100%	T 60% T 70% T 80%	T 100%	T 100%	T 100%	T 100%

Fig. 13. A graph shows the simulation of translation motion best cases in terms of illumination evaluation levels: "daylit", "partially daylit" and "over lit" areas.

illuminance resulting from rotation and translation motion in Fig. 14, it shows how each type of kinetic motion could best perform all the time according to solar angles, altitude and azimuth.

This optimization process of the best possible kinetic hexagonal skin configuration that produced the highest daylighting performance sometimes resulted in two or more different configurations. These two different configurations could be open or closed cell, therefore the author began to classify them into two groups (preferably closed and preferably opened). This classification opens up a large platform of applications for different purposes: closed for privacy and open for external interaction. Graphical analysis in Fig. 15 and 16 aims is to present kinetic configurations produced the highest daylighting performance side by side to allow the reader to see the effect of the motion parameters on the daylighting performance.

5. Discussion

This paper summarizes the simulation results of kinetic skins in daylighting environment for south-facing office spaces. In general, results indicate a major influence of kinetic skin patterns and type of motion on daylighting performance. It was found that all kinetic skins helped improve the visual environment. The type and direction of motion of the same pattern affects daylighting qualities inside the space, due to two main variables, first, the three dimensional qualities some types of motion give which provides shade and shadow and prevent direct sunlight; second, the pattern distribution improves the uniformity level of daylight to the recommended level in the space.

Kinetic skins could play an essential role as daylight solar screens as well as sun protection devices if both daylight and solar gain were taken into design consideration. Moreover, kinetic skins control the excessive sunrays and protected the working plane from direct sun and eliminated sources of glare. Accordingly, five main factors need to be taken into consideration in designing kinetic skins: 1 – form and Size of kinetic pattern; 2 – type and direction of motion; 3 – double skin spacing; 4 – ability to block direct sun light; 5 – improve daylight quality; and 6 – maintain a minimum level of contact with outside.

The current findings empirically confirm previous theoretical approach of kinetic facade. According to Fox (2003), the motion and changing position of the surface defined the positioning and pattern relative to the external environment. This results in higher or lower levels of solar radiation in the space. For instance, the surface pattern was identified for a translational kinetic motion, which was flat, single-curved or double-curved. This finding illustrates the advantages of kinetic facade in environmental control (Ramzy and Fayed, 2011).

The method involved different kinds of constraints, parameters and strategies, which created different options and variables to assist designers to make effective decisions at the early design stage. Each type of motion has its morphology, aesthetics and effect which helps in the decision

Table 3
Comparison of daylighting performance for the best-possible results of the three systems performed at four times of the year.

		Percentage of "Daylit" area as a function of Rotation and Translation motion				
		Base case	Rotation motion	Angle of rotation	Translation motion	Translation displacment percentage
March	9:00 AM	39.58	100.00	R60.0- R75-R120	58.33	100 % opened (Fully opened)
	12:00 PM	60.42	97.92	R45.0	93.75	100 % opened (Fully opened)
	3:00 PM	39.58	100.00	R60.0- R75- R105	93.75	100 % opened (Fully opened)
June	9:00 AM	29.17	100.00	R90.0	83.33	100 % opened (Fully opened)
	12:00 PM	54.17	100.00	R60.0- R75- R90-R105-R	89.58	100 % opened (Fully opened)
	3:00 PM	29.17	100.00	R60.0- R75- R105	68.75	100 % opened (Fully opened)
September	9:00 AM	52.08	100.00	R60.0- R75	81.25	80 % or 90% opened (Partially opened) or 100 % opened (Fully opened)
	12:00 PM	68.75	91.67	R45.0-R60	87.50	60 % or 70% or 80 % opened (Partially opened)
	3:00 PM	39.58	97.92	R75-R90	83.33	100 % opened (Fully opened)
December	9:00 AM	52.08	91.67	R45.0	62.50	100 % opened (Fully opened)
	12:00 PM	68.75	91.67	R45.0	95.83	100 % opened (Fully opened)
	3:00 PM	39.58	97.92	R60.0	75.00	100 % opened (Fully opened)

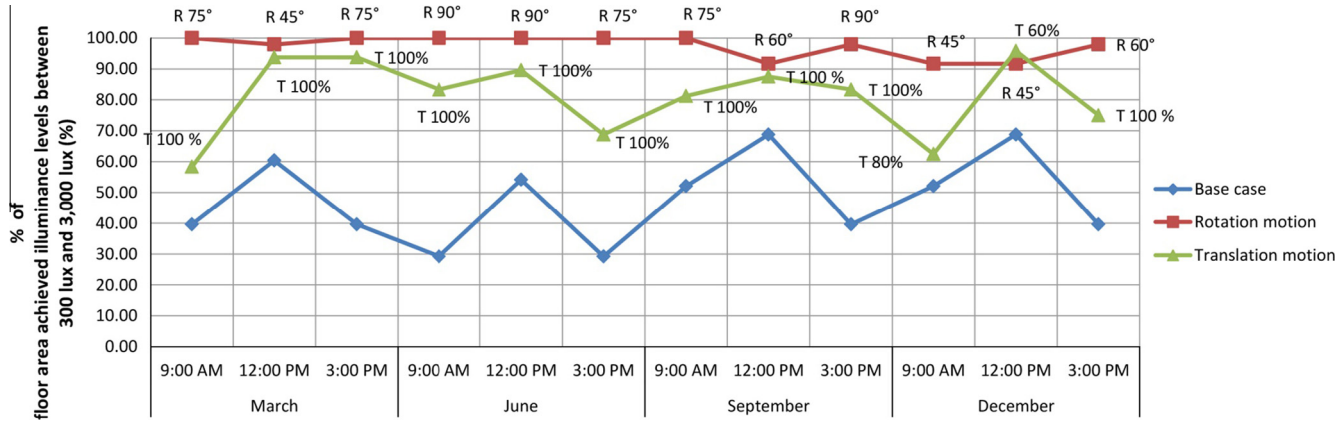


Fig. 14. Comparison between the best-possible results of the three systems in terms of the Percentage of Floor Area achieving luminance levels between 300 and 3000 lux as a function of simulation time.

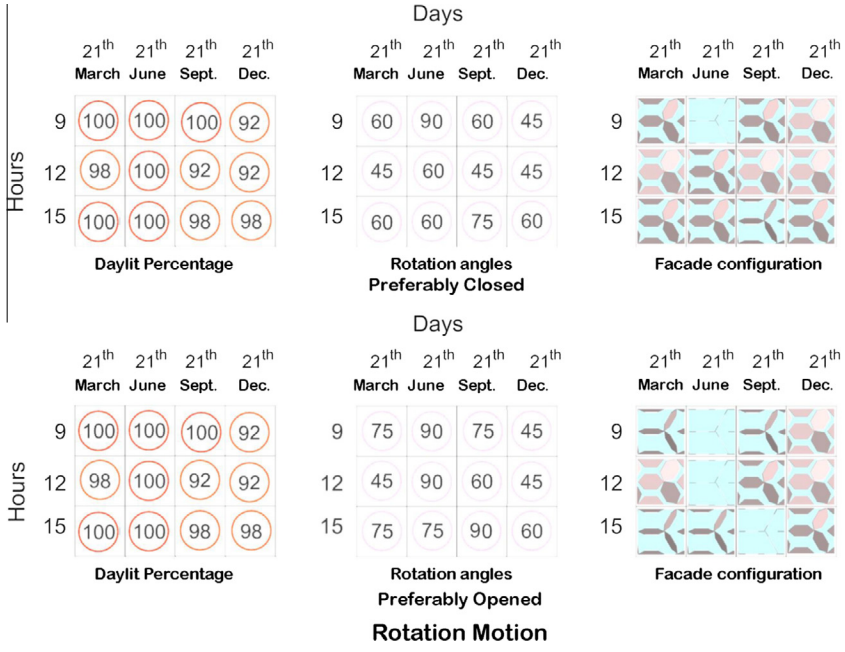


Fig. 15. Daylit percentage as a result of best rotation motion configuration classified into two groups: preferably closed and preferably opened.

making process at the early design stage. Parametric models are used to fine tune for the best geometrical attributes to design for a particular case. However, parametric simulation is not the most efficient way to find an optimal solution given the infinite possibilities of skin configurations. One of the challenges of an effective simulation tool is not only the ability to evaluate accurately but to speed up and simplify the process used by the tool for such dynamic design evaluation. Solving the DIVA component scripting problem will prove the efficiency of the system in a more reliable and acceptable discussion. One of the most important outcomes of this study is providing a tool for the designer to apply and evaluate kinetic motions for effective daylight control in the early design stage. Kinetic skins may present solutions for better energy-performing architecture, but they cost a lot of money and can be difficult to maintain. Research must keep exploring the performance of these kinds of skins independently along with comparing them to feasibility models for cost and development. Accordingly, further evaluation will be conducted using digital fabrication and physical modeling to know better the possibilities of these motions working as intended. According to Ramzy and Fayed (2011)) such an evaluation will be compared and analyzed in the context of kinetic performance for environmental control.

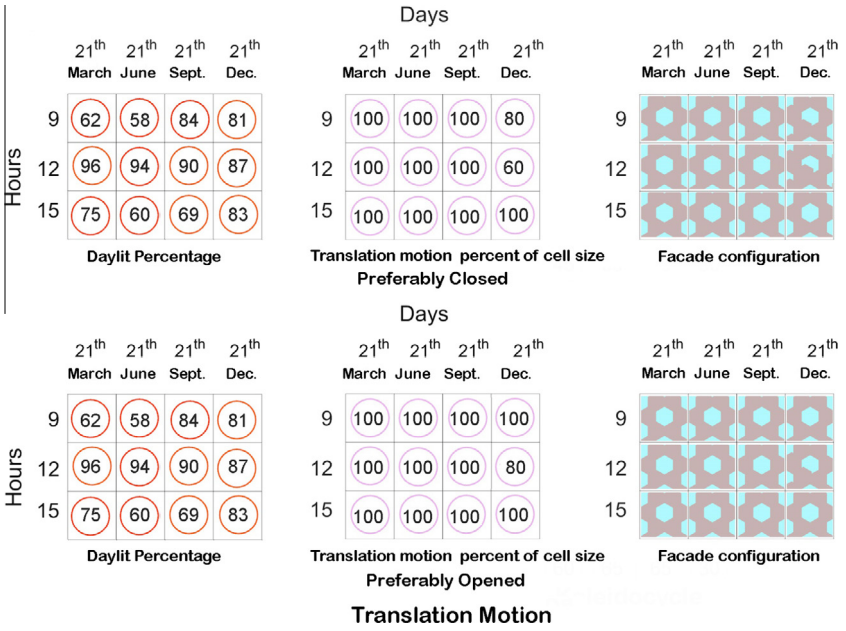


Fig. 16. Daylit percentage as a result of best translation motion configuration classified into two groups: preferably closed and preferably opened.

6. Conclusions

This research investigates the integration of parametric design definitions and environmental software, which can assist in the development of kinetic facade's design. The method involved different kinds of constraints, parameters and strategies, which created different options and variables to assist designers to make effective decisions at the early design stage.

Designing kinetic skins requires studying the performance around the year in both hot and cold periods. Therefore, Rotational motion could perform well around the year as evinced by daylighting simulations as they helped block all the sunrays all the time. The Rotational motion improved daylighting by approximately 50% in summer & spring and about 30% in autumn and winter compared to the base case. This change in performance was considered "Significant" as the values of "daylit" areas increased to almost 100%. On the other hand, the translational motion allowed some sunshine to enter the space at 9 am & 3 pm, and couldn't fully prevent it from direct sun rays. However it improved daylighting by only 50% in summer & spring and 20% in winter, Fig. 16. In conclusion, Rotational motion provided a well-lit spaces and better illumination levels than translational motion. Rotation and translation motions can alter different possible geometries, in response to daylight conditions producing various configurations. As For the scaling motion configuration, it is important to know the potential materials that can be associated with it in order to select the right material in Diva application. Compound kinetics that results from pairing the base kinetic transformations of translation, rotation and scaling can also be tested in future research. However, different possibilities due to environmental factors, such as thermal conditions, can also be integrated, adopting a similar process. These factors may affect the categories of configuration of kinetic pattern.

One of the most important outcomes of this study is providing a toolkit for designers to apply and evaluate kinetic motions for effective daylight control in the early design stage. Each type of motion has its morphology, aesthetics and effect which helps in the decision making process at the early design stage. Further evaluation will be conducted using digital fabrication and physical models to know better the possibilities of these motions working as intended. This evaluation will be compared and analyzed in the context of kinetic performance for environmental control.

This research presents an integration of three different digital tools, Rhino, Grasshopper, and DIVA. They were used to develop one algorithm that is intended to be used for optimal rotation angle and displacement search. The technical difficulties experienced resulted in carrying out manual simulation runs for the search for an optimal scheme. Some of the simulated schemes showed success at certain times of the year. However, manual simulation is not the most efficient way to find an optimal solution given the infinite possibilities of skin configurations. Solving the DIVA component scripting problem will prove the efficiency of the system in a more reliable and acceptable discussion.

Kinetic skins may present solutions for better energy-performing architecture, but they cost a lot of money and can be difficult to maintain. Research must keep exploring the performance of these kinds of skins independently along with comparing them to feasibility models for cost and development.

The integration of inputs from all previous disciplines may result in a system that is cost effective and has a short payback period. However, the architect should be a central part of the design process to support new trends in form generation such as complex geometry.

References

Baldinelli, G., 2009. Double skin façades for warm climate regions: analysis of a solution with an integrated movable shading system. Build. Environ. 44, 1107–1118.

Beesley, P., Hirosue, J., Trankle, R., Turner, C., 2006. Responsive Architectures: Subtle Technologies. Riverside Architectural Press.

Bougiatioti, F., Evangelinos, E., Poulakos, G., Zacharopoulos, E., 2009. The summer thermal behaviour of "skin" materials for vertical surfaces in Athens, Greece as a decisive parameter for their selection. Sol. Energy 83, 582–598.

Favoino, F., Goia, F., Perino, M., Serra, V., 2014. Experimental assessment of the energy performance of an advanced responsive multifunctional façade module. Energy Build 68 (Part B), 647–659.

Fox, M., 2003. Kinetic architectural systems design. In: Kronenberg, R. (Ed.), Transportable Environments Book 2. Taylor & Francis.

Fox, M., Kemp, M., 2009. Interactive Architecture. Princeton Architectural Press, New York.

Freewan, A.A., 2014. Impact of external shading devices on thermal and daylighting performance of offices in hot climate regions. Sol. Energy 102, 14–30.

GhaffarianHoseini, A., Dahlan, N., Berardi, U., GhaffarianHoseini, A., Makaremi, N., GhaffarianHoseini, M., 2013. Sustainable energy performances of green buildings: a review of current theories, implementations and challenges. Renew. Sustain. Energy Rev. 25, 1–17.

Godfried, A., 2011. The role of simulation in performance based building. Building Performance Simulation for Design and Operation. Spon Press, pp. 15–36.

Greenberg, D., Kevin Pratt, K., Hencey, B., Jones, N., Schumann, L., Dobbs, J., et al., 2013. Sustain: an experimental test bed for building energy simulation. Energy Build. 58, 44–57.

Heidarinejad, M., Dahlhausen, M., McMahon, S., Pyke, C., Srebric, J., 2014. Cluster analysis of simulated energy use for LEED certified U.S. office buildings. Energy Build. 85, 86–97.

Lim, Y.-W., Kandar, M.Z., Ahmad, M.H., Ossen, D.R., Abdullah, A.M., 2012. Building façade design for daylighting quality in typical government office building. Build. Environ. 57, 194–204.

Liu, M., Wittchen, K.B., Heisel, P.V., 2014. Development of a simplified method for intelligent glazed façade design under different control strategies and verified by building simulation tool BSim. Build. Environ., 31–38

Mahmoud, A.H., 2011. An analysis of bioclimatic zones and implications for design of outdoor built environments in Egypt. Build. Environ. 46, 605–620.

Mira, L.A., Thrall, A.P., De Temm, N., 2014. Deployable scissor arch for transitional shelters. Automat. Constr. 43, 123–131.

Moloney, J., 2011. Designing Kinetics for Architectural Facades: State Change. Routledge, New York.

Moschetti, R., Mazzarella, L., Nord, N., 2015. An overall methodology to define reference values for building sustainability parameters. Energy Build. 88, 413–427.

Moya, Q., Pons, O., 2014. Improving the design and production data flow of a complex curvilinear geometric Glass Reinforced Concrete façade. Automat. Constr. 38, 46–58.

Nielsen, M.V., Svendsen, S., Bjerreg, L., 2011. Quantifying the potential of automated dynamic solar shading in office buildings through integrated simulations of energy and daylight. Sol. Energy 85, 757–768.

O'Brien, W., Kapsis, K., Athienitis, A.K., 2013. Manually-operated window shade patterns in office buildings: a critical review. Build. Environ. 60, 319–338.

Oosterhuis, K., Xia, X., 2007. Interactive Architecture. Episode, Rotterdam, Netherlands.

Rafael, U.S., 2010. Parametric performative systems: designing a bioclimatic responsive skin. Int. J. Archit. Comput. 8 (3), 279–300.

Ramzy, N., Fayed, H., 2011. Kinetic systems in architecture: new approach for environmental control systems and context-sensitive buildings. Sustain. Cities Soc. 1 (3), 170–177.

Sabry, H., Sherif, A., Gadelhak, M., Aly, M., 2014. Balancing the daylighting and energy performance of Solar Screens in residential desert buildings: examination of screen axial rotation and opening aspect ratio. Sol. Energy 103, 364–377.

Schumacher, M., Schaeffer, O., Vogt, M.M., 2010. Move: Architecture in Motion-Dynamic Components and Elements. Walter de Gruyter.

Sharaidin, K., Burry, J., Salim, F., 2012. Integration of digital simulation tools with parametric designs to evaluate kinetic facades for daylight, performance, simulation, prediction, and evaluation. eCAADe 30, 2.

Shen, H., Tzempelikos, A., 2012. Daylighting and energy analysis of private offices with automated interior roller shades. Sol. Energy 86, 681–704.

Sherif, A.H., Sabry, H.M., Gadelhak, M.I., 2012a. The impact of changing solar screen rotation angle and its opening aspect ratios on daylight availability in residential desert buildings. Sol. Energy 86, 3353–3363.

Sherif, A., El-Zafarany, A., Arafa, R., 2012b. External perforated window Solar Screens: the effect of screen depth and perforation ratio on energy performance in extreme desert environments. Energy Build. 52, 1–10.

Sherif, A., Sabry, H., Rakha, T., 2012c. External perforated Solar Screens for daylighting in residential desert buildings: identification of minimum perforation percentages. Sol. Energy 86, 1929–1940.

Tzempelikos, A., Athienitis, A.K., Karava, P., 2007. Simulation of façade and envelope design options for a new institutional building. Sol. Energy 81, 1088–1103.